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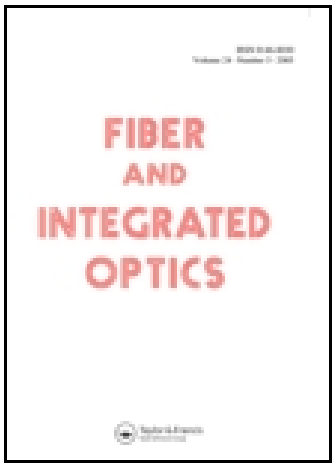

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Guiding Properties of a Tapered Photonic Crystal Fiber Compared with Those of a Tapered Single-Mode Fiber

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We have fabricated tapered photonic crystal fibers using a fusion splicer and experimentally observed the near-field mode distribution and the beam divergence of it. We have also compared characteristics of the tapered photonic crystal fiber with those of a tapered standard single-mode fiber. Unlike a tapered standard single-mode fiber, the mode field profile of a tapered photonic crystal fiber shows a good confinement of its field within the core region. The numerical apertures of tapered photonic crystal fibers are increased as the diameter of the fiber is decreased.

Keywords tapered fiber, photonic crystal fiber, near field, mode distribution, beam divergence, guiding properties

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Introduction

Unlike a standard optical fiber whose core and cladding are made of different materials, a photonic crystal fiber (PCF) is made of a single material with many air holes in it [1]. Also known as the holey optical fiber, PCF is fabricated by introducing a defect or a missing hole into an array of regularly spaced tiny air holes running along its propagation axis. Thus, light is guided along the defect throughout the fiber length. Recently, PCF has attracted a lot of attention because of its unusual optical properties such as very large mode area, extra large chromatic dispersion, and a wide-range, single-mode operation

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[1–4]. These properties are affected by the refractive index of the cladding region determined by the regularly spaced tiny air holes. This new refractive index structure is potentially very useful for making novel fiber devices, e.g., dispersion managed fibers, fiber gratings, and fiber amplifiers.

Generally, tapered optical fibers are used in optical couplers, wavelength filters, and beam expanders [5]. The tapered optical fibers are primarily used in order to use the efficient coupling of light from an optical fiber into many integrated optical devices, e.g., laser diodes, arrayed waved guide gratings, modulators, or semiconductor optical amplifiers. However, the tapered single-mode fiber (SMF) has some problems in coupling light directly into a waveguide [6]. A tapered SMF restricts its single-mode guiding properties to a limited wavelength region [7]. As the spot size of a tapered SMF is not proportional to the outer diameter of the tapered SMF, it is difficult to predict the linear relationship of the spot size and the beam divergence of a guided mode from the outer diameter of a tapered SMF [8, 9]. Thus, in order to overcome these problems of the tapered SMF, a new mode conversion method using a tapered PCF was proposed. In this article, we have made a novel tapered optical fiber using a PCF and experimentally investigated the unusual guiding properties of it. We have measured the near-field mode distributions and the corresponding beam divergences of various tapered PCFs. Likewise, these characteristics were compared with those of a tapered SMF. We have verified the recently reported simulation results demonstrating spot-size reduction and significant numerical aperture increase in a tapered PCF [10, 11].

Experimental Results

A tapered optical fiber was prepared using a fusion splicer (Furukawa S174H) and a fiber cleaver (FITEL S324). The optical fiber was melted with the heat from the arc in a fusion splicer, while one end of the optical fiber is fixed and the other end is pulled with a constant force. To control the shape of the tapered fiber, three parameters were considered: arc power, arc duration time, and the pulling force. These three parameters are interrelated, so it is difficult to find the linear relation among them. To investigate the field propagation of the tapered optical fiber, the end face of the tapered optical fiber was prepared by cutting the tapered region with a fiber cleaver. The cleaver was set such that its blade barely touched tapered fiber. With these methods, various sizes of tapered SMFs and PCFs were obtained. The tapered length of each SMF and PCF is about 800 (m, while the outer diameter (OD) of the tapered region is about 20 (m. The structure of the tapered PCF is observed to be almost the same as the original structures of the PCF. The PCF was made using a preform that has five layers of hollow cylinders with 3 mm OD and a solid cylinder at the center. The outer diameter of the original PCF is 156 μm, while the pitch between air holes in the hexagonal structure is about 8 μm. Here, the core diameter (CD) of a PCF is considered to be twice the size of the pitch between air holes. Figure 1(a) shows the image of the cleaved end surface of the PCF, whereas Fig. 1(b) shows a side view of the tapered PCF. As the distribution of the air holes in the original PCF is not regular, we believe that the dominant guiding mechanism in our PCF is the index-guiding effect rather than the photonic band gap effect. The sample we used is a single-mode PCF both at 635 nm and 1552 wavelengths.

In order to measure the guiding properties of the tapered PCF, laser lights were launched on the other cleaved end surface of the PCF using a lensed single mode fiber. The near-field image of the tapered end face was then measured using a 60$\times$ objective lens with a Vidicon tube camera (Hamamatsu M2741-03). The mode field profiles can be

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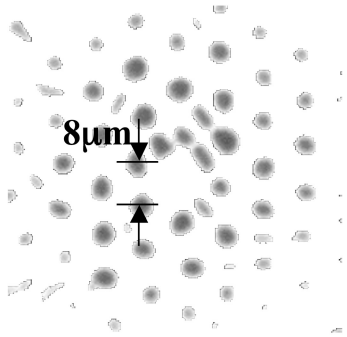
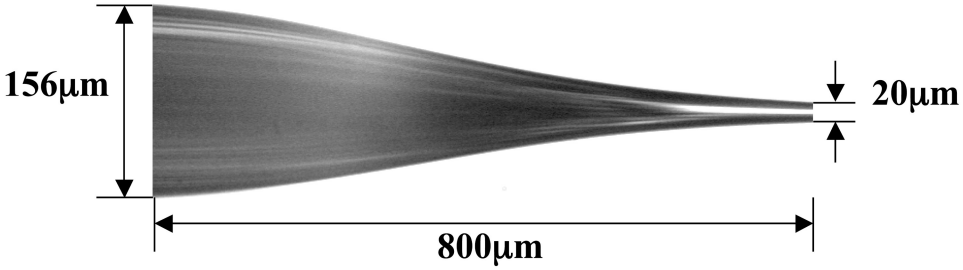


(a)



(b)

Figure 1. (a) The cut-view microscope image of the PCF; (b) The side-view microscope image of the tapered PCF. The tapered length of the PCF is 800 μm whereas the tapered outer diameter (OD) is 20 μm.

imaged onto the Vidicon tube camera with hardly any deformation of image. For this PCF, two different light sources were used (635 nm and 1552 nm laser diodes). In Figure 2 we compared the spot size of the tapered PCF with that of the tapered SMF. It shows near-field mode distributions of tapered SMFs and PCFs with four different ODs. The mode field profile of a standard SMF (Corning SMF-28) is shown in Figure 2(a) for the two different light sources. We have carefully adjusted the launching condition of a laser light source to have as much symmetric mode profile as possible at 635 nm wavelength even though the fiber supports multimodes at that wavelength. Figure 2(b) shows mode profiles of a tapered SMF whose OD is 20 μm when lights at 635 nm and 1552 nm wavelengths are launched to the fiber. Unlike the general guiding properties of an SMF, the tapered SMF remained as a multimode waveguide at 1552 nm wavelength because all the guided modes are guided by the glass–air interface at the cladding surface. As expected for a tapered SMF, these show that the mode field diameters are not proportional to the OD of a tapered SMF. Nevertheless, the PCF exhibited different mode field characteristics when compared with an SMF. Figures 2(c) and 2(d) compare the mode field characteristics of the PCF with those of an SMF at two different wavelengths. Figure 2(c) is the mode field profile of a PCF with its OD of 156 μm and CD of 16 μm. On the other hand,

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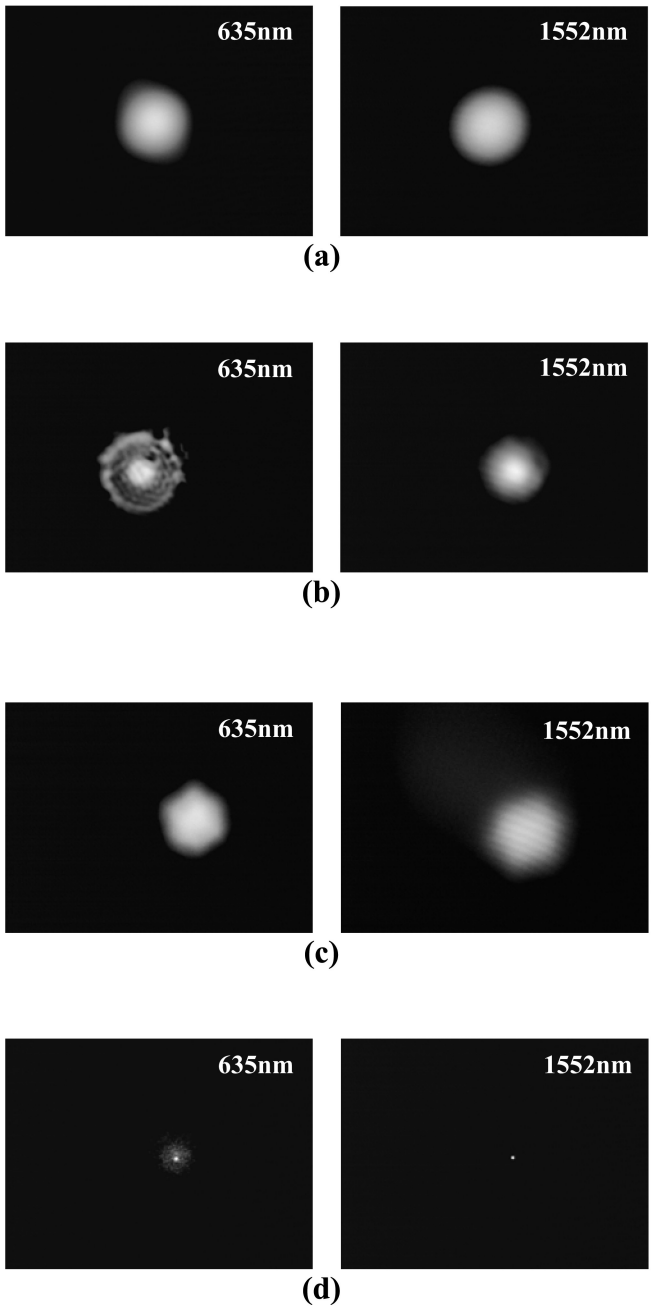

Figure 2. The near-field mode profiles of (a) SMF; (b) tapered SMF; (c) PCF; (d) tapered PCF at 635 nm and 1552 nm wavelengths.

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Figure 2(d) is the mode field profile of a tapered PCF with its OD of 20 μm and CD of about 2 μm. These results confirmed that a PCF and a tapered PCF only support the fundamental mode in a wide wavelength range, and the reduction of the spot size is proportional to the OD of a tapered PCF.

Figure 3 shows the one-dimensional mode field profiles obtained from the images in Figures 2(a), 2(b), 2(c), and 2(d) at 1552 nm wavelength. Figure 3(a) shows the difference in its mode profile for an SMF before and after the tapering process. It clearly shows that it is a multimode waveguide fiber at 1552 nm wavelength when the OD is tapered to 20 μm. Even though it is not shown here, we have observed that it supports many modes at 635 nm wavelength. The ratio of the full-width half-maximum (FWHM) of the guided modes for the original SMF and the tapered SMF is about 1/1.5, while the OD of the tapered SMF is reduced by the ratio of 1/6.25. There is almost no change in full-width 1/10 maximum of the two fields in Figure 3(a). Spot size reduction in a tapered PCF is shown in Figure 3(b). The ratio of the full-width half-maximum of the guided mode between the two fibers is about 1/8, and so is the ratio of OD.

The spot sizes of tapered PCFs with various CDs are measured and plotted in Figure 4. Here, the spot size is defined as the FWHM of the guided mode profile, and the CD is defined as twice the size of the pitch between air holes. Unlike the SMF cases [5–8], the relation between the spot size and the CD of a PCF is quite linear until the core diameter becomes close to the wavelength of guided light. However, it is observed that the spot size becomes a little bit larger than the CD when the CD becomes compatible to the wavelength of the guided mode (1552 nm). We believe that it is mostly due to the leakage of light across the air holes around the core as the size of the air holes becomes close to the wavelength of guided light. According to this figure, 2.8 μm is the minimum spot size we can obtain by using this tapering method with a PCF. It is little bit larger than the diffraction-limited spot size we can obtain with light at 1552 nm wavelength.

To investigate the numerical aperture (NA) of the tapered optical fiber, we have measured the spot sizes of the diverging beams from the end faces of tapered optical fibers by using a 60$\times$ objective lens and a Vidicon tube camera. Several beam profiles are captured by the Vidicon tube camera when the positions of the imaging camera and the objective lens are fixed while the end surface of the sample fiber is moved back off from the objective lens. Figure 5 shows that the half-width half-maximum (HWHM) of the spot size is almost linearly increased for diverging beams from the end surface of a tapered fiber as the distance between the objective lens surface and the end face of the fiber is increased. Slopes that correspond to the NAs of diverging beams from the three different CD sizes of tapered PCFs (17.0 μm, 12.2 μm, and 6.4 μm) are calculated from the measured data. When the OD of the tapered PCF is 20 μm, NA is too large to be measured at 1552 nm wavelength. From these results, we have confirmed that the numerical apertures are increased almost linearly as ODs of the tapered PCF are decreased.

Conclusions

We have fabricated tapered PCFs by using a fusion splicer and a fiber cleaver. Experimental observation of the near-field mode profile of the PCF and tapered PCF showed that the PCF is able to restrict its mode field profile within the core diameter of the tapered PCF. The relation between the spot size and the core diameter is linear. The mode pattern of the original PCF and tapered PCF support only single modes at both 1552 nm and 635 nm wavelengths. Therefore, the tapered PCF can be used very effectively for mode conversion applications. Meanwhile, a tapered SMF has single-mode

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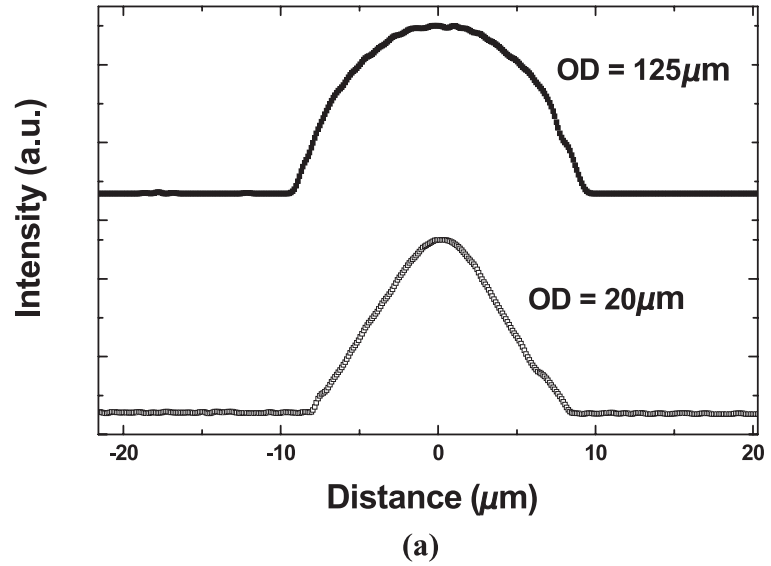
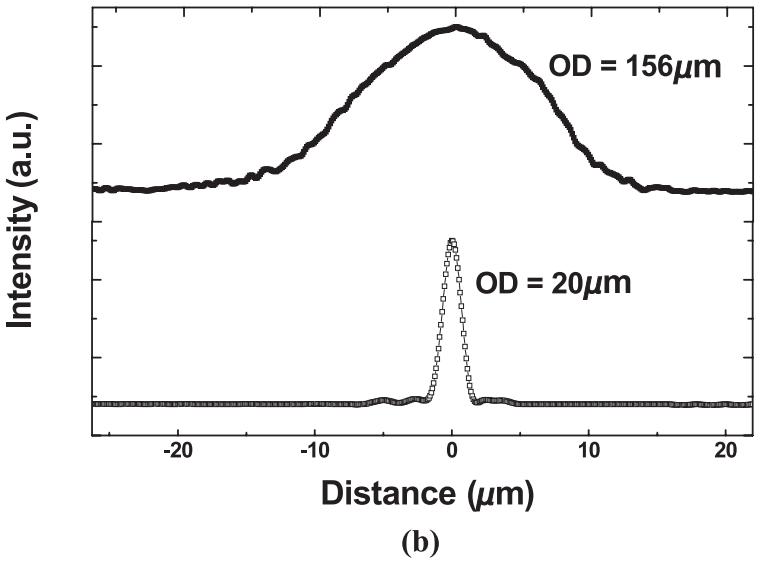


(a)



(b)

Figure 3. (a) The mode field profile of the original SMF and the tapered SMF shown in Figure 2; (b) the mode field profile of the original PCF and the tapered PCF shown in Figure 2 at 1552 nm wavelength.

guiding properties in a limited wavelength region and its spot size is not proportional to the OD of a tapered SMF. Likewise, we have confirmed that the numerical apertures are increased by the decreasing OD of a tapered PCF. These properties are useful in various applications for the efficient coupling of light from an optical fiber into various planar waveguide devices.

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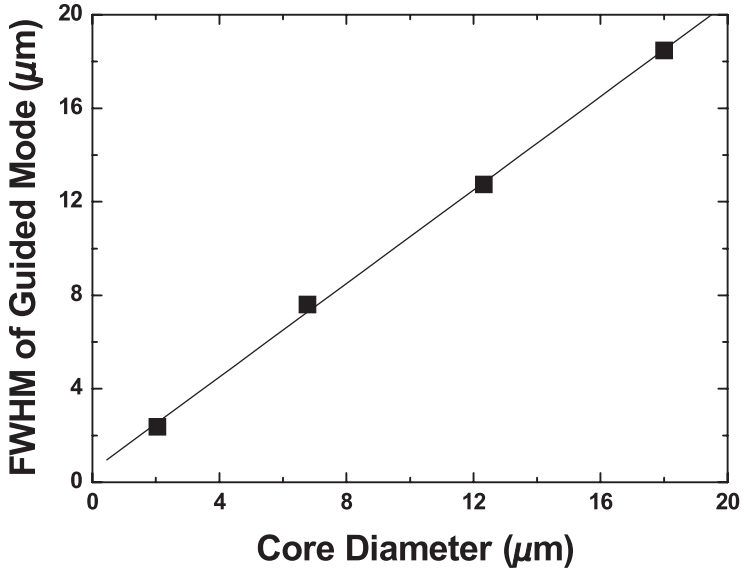

Figure 4. Spot size (full-width half-maximum of the guided mode field) for a tapered PCF as a function of the core diameter (CD) of a tapered PCF at 1552 nm wavelength. The outer diameter (OD) of the original PCF before tapering process is 146 μm, while the pitch between air holes in the hexagonal structure is about 5 μm.

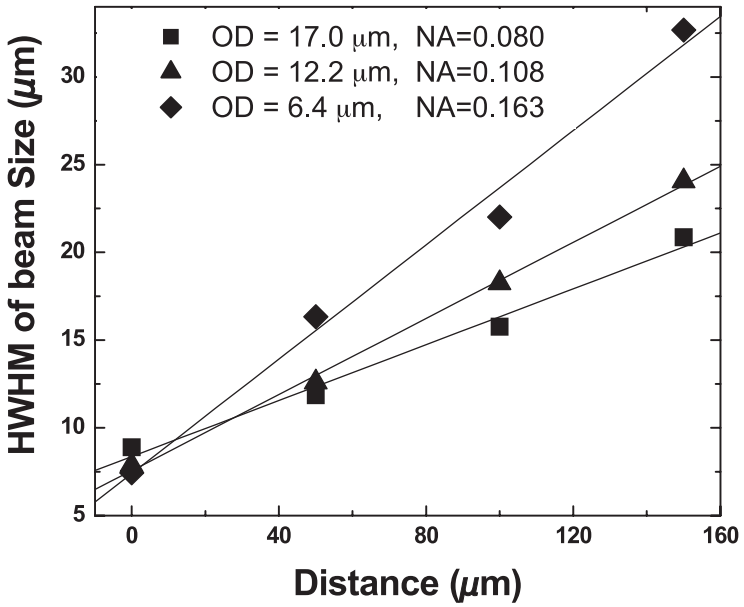

Figure 5. Half-width half-maximum (HWHM) of diverging beam as a function of the distance between the objective lens and the end face of a tapered PCF for various CDs of PCF.

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Biography

Youngchun Youk was born in Jeonju, South Korea, in 1975. He received his B.S. degree in physics from Chonbuk National University, Chonbuk, South Korea, and MS degree in information and communications from Gwangju Institute of Science and Technology (GIST), Gwangju, South Korea in 1998 and 2001, respectively. He is pursuing his PhD degree in information and communications from GIST. Currently, he is working on studying tapered optical fiber, lensed fiber, and confocal microscopy, refractive index measurement on various photonic devices.

Kun Wook Park was born in Andong, South Korea, in 1973. He received his B.S. degree in electronic engineering from Kyungpook National University, Kyungpook, South Korea, and MS degree in information and communications from Gwangju Institute of Science and Technology (GIST), Gwangju, South Korea in 1999 and 2001. Currently he has been working at storage media group, LG Electronics Institute of Technology, Seoul, South Korea.

Dug Young Kim was born in Seoul, Korea, in 1963. He received his B.S. degree in physics from Sogang University, South Korea in 1986. After he received his PhD from the Optical Sciences Center of the University of Arizona in 1994 he joined the Photonics Research Lab of the University of Melbourne, Australia as a research fellow. Since 1997 he has been working at Gwangju Institute of Science and Technology (GIST), Gwangju as an assistant professor. His current research interests are nonlinear optics, optical short pulse generation and soliton propagation, optical measurements on specialty optical fibers, and various photonic devices for optical communication applications.

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